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$^1P_1$ charmonium production at the Tevatron

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ABSTRACT

The production of the $^1P_1$ charmonium state, h_c, at large-p_T at the Tevatron is considered. The colour-octet contributions to this state are found to be dominant and give a reasonably large rate for the production of h_c. This should make it feasible to look for this resonance in the $J/\psi + \pi$ decay channel. This production rate is a prediction of NRQCD, and the observation of the h_c at the Tevatron can, therefore, be used as a test of the colour-octet predictions of NRQCD.

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The production of quarkonia has conventionally been described in terms of the colour-singlet model [1, 2], which uses a non-relativistic approximation to describe the binding of the heavy-quark pair produced via parton-fusion processes into a quarkonium state. The heavy-quark pair is projected onto a physical quarkonium state using a colour-singlet projection and an appropriate spin-projection. The failure of this model in explaining the data on the inclusive large-p_T J/ψ production cross-section measured by the CDF experiment [3] has led to a major revision of the theory of quarkonium formation. The colour-singlet model is an approximation which works well only when the relative velocity v between the quarks in the quarkonium state can be completely neglected. It is possible to include the effects coming from higher orders in a perturbation series in v in the framework of an effective field theory called non-relativistic QCD (NRQCD) [4].

NRQCD is an effective field theory derived from the full QCD Lagrangian by neglecting all states of momenta larger than a cutoff of the order of the heavy quark mass, M, [5] and accounting for this exclusion by introducing new interactions in the effective Lagrangian, which are local since the excluded states are relativistic. Beyond the leading order in $1/m$ the effective theory is non-renormalisable. The physical quarkonium states can then be expanded in terms of its Fock-components in a perturbation series in v, and it then turns out that the $Q\bar{Q}$ states appear in either colour-singlet or colour-octet configurations in this series. Of course, the physical state is a colour-singlet so that a colour-octet $Q\bar{Q}$ state is connected to the physical state by the emission of one or more soft gluons. In spite of the non-perturbative nature of the soft gluons emitted, it turns out that the effective theory still gives us some useful information about the intermediate octet states. This is because the dominant transitions from colour-octet to physical colour-singlet states are *via* $E1$ or $M1$ transitions with higher multipoles being suppressed by powers of v. It then becomes possible to use the usual selection rules for these radiative transitions to keep account of the quantum numbers of the octet states, so that the short-distance coefficient corresponding to the octet state can be calculated and its transition to a physical singlet state can be specified by a non-perturbative matrix element. The cross-section for the production of a meson H then takes on the following factorised form:

$$\sigma(H) \;=\; \mathrm{Im} \sum_{n=\{\alpha,S,L,J\}} \frac{F_n}{m^{d_n-4}} \langle \mathcal{O}_\alpha^H(^{2S+1}L_J) \rangle \tag{1}$$

where F_n's are the short-distance coefficients and $\mathcal{O}_n$ are local 4-fermion operators, of naive dimension d_n, describing the long-distance physics. The cutoff-dependence of F_n is compensated by that of the long-distance matrix elements.

The importance of colour-octet components was seen [6] in the phenomenology of P-state charmonium production at large p_T in the Tevatron data. These processes do not have a consistent description in terms of colour singlet operators alone [7]. However, even for the direct production of S-states such as the J/ψ or ψ', where the

colour singlet components give the leading contribution in v, the inclusion of sub-leading octet states was seen to be necessary for phenomenological reasons [8]. The long-distance matrix elements are not calculable, and a linear combination of octet matrix-elements have been fixed by fitting to the Tevatron data [9]. Independent tests of the S-state colour octet enhancement are important and recent work shows that a different linear combination of the same colour octet-matrix elements that appear in the Tevatron analysis also appears in the analyses of photoproduction [10] and hadroproduction experiments [11]. These analyses provide an important cross-check on the colour-octet contributions. Other production modes like J/ψ production in low-energy $e^+ - e^-$ collisions [12], on the Z-peak at LEP [13] and in Υ [14] decays have been considered, with the purpose of determining the magnitude of the octet contribution.

In this letter, we compute the large-p_T production cross-section for the ${}^1P_1$ charmonium state, h_c. The production of this resonance is interesting in its own right : charmonium spectroscopy [15] predicts this state to exist at the centre-of-gravity of the $\chi_c({}^3P_J)$ states. The E760 collaboration at the Fermilab have reported [16] the first observation of this resonance but this needs further confirmation. It is, therefore, interesting to determine the theoretical production rate for this resonance at the Tevatron and to know whether there is any chance that its existence can be confirmed. From our point of view the production of the ${}^1P_1$ is interesting for yet another reason. Being a P-state, the leading colour-singlet contribution is already at $O(v^2)$, and at the same order we have the octet production of the ${}^1P_1$ state through an intermediate ${}^1S_0$ state. As we shall see later, we can infer the non-perturbative matrix elements for the production of h_c from the matrix-elements of other states. One channel which may be suitable for the detection of the h_c is its decay into a $J/\psi + \pi$. Armed with the non-perturbative matrix elements we can *predict* the number of $J/\psi + \pi$ events in the total sample of J/ψ's accumulated by the Tevatron experiments, provided we know the decay branching fraction for $h_c \to J/\psi + \pi$. This latter number has been estimated from spectroscopy We believe that with these inputs, a reasonably solid prediction of the production cross-section of the ${}^1P_1$ charmonium state is possible within the NRQCD framework. It is worth mentioning again that we are considering the large-p_T production of this state and therefore, we are on firm grounds in using the factorisation relation of the kind shown in Eq. 1.

The subprocesses that we are interested in are the following:

$$\begin{aligned} g + g &\to {}^1P_1^{[1]} + g, \\ g + g &\to {}^1S_0^{[8]} + g, \\ q(\bar{q}) + g &\to {}^1S_0^{[8]} + q(\bar{q}), \\ q + \bar{q} &\to {}^1S_0^{[8]} + g. \end{aligned} \tag{2}$$

The ${}^1S_0^{[8]} \to h_c$ is mediated by a gluon emission in a $E1$ transition. The large-p_T

hadronic production cross-section is given as

$$\frac{d\sigma}{dp_T}(p\bar{p} \to {}^1P_1X) =$$
$$\sum \int dy \int dx_1 x_1 G_{a/p}(x_1) x_2 G_{b/\bar{p}}(x_2) \frac{4p_T}{2x_1 - \bar{x}_T e^y} \frac{d\hat{\sigma}}{d\hat{t}}(ab \to {}^2S + 1L_J c). \quad (3)$$

In the above expression, the sum runs over all the initial partons contributing to the subprocesses; $G_{a/p}$ and $G_{b/\bar{p}}$ are the distributions of partons a and b in the hadrons with momentum fractions x_1 and x_2, respectively. Energy-momentum conservation determines x_2 to be

$$x_2 = \frac{x_1 \bar{x}_T e^{-y} - 2\tau}{2x_1 - \bar{x}_T e^y}, \quad (4)$$

where $\tau = M^2/s$, with M the mass of the resonance, s the centre-of-mass energy and y the rapidity at which the resonance is produced.

$$\bar{x}_T = \sqrt{x_T^2 + 4\tau} \equiv \frac{2M_T}{\sqrt{s}}, \qquad x_T = \frac{2p_T}{\sqrt{s}} \quad (5)$$

The expressions for the singlet and the octet subprocess cross-sections, $d\hat{\sigma}/d\hat{t}$, are given in Refs. [17] and [9], respectively.

The production cross-section for the ${}^1P_1$ state is fully specified, once we have specified the colour-singlet matrix element for the ${}^1P_1$ state $\left\langle \mathcal{O}_1^{h_c}({}^1P_1) \right\rangle$ and the value for the colour-octet matrix element that takes the octet ${}^1S_0$ state to a h_c, $\left\langle \mathcal{O}_8^{h_c}({}^1S_0) \right\rangle$. We note that the matrix element of the singlet ${}^1P_1$ state is related to the derivative of the wavefunction of at the origin by

$$\left\langle \mathcal{O}_1^{h_c}({}^1P_1) \right\rangle = \frac{27}{2\pi}|R'(0)|^2. \quad (6)$$

The Tevatron data on χ_c production fixes [9] the colour-octet matrix element which specifies the transition of a ${}^3S_1$ octet state into a ${}^3P_J$ state. We would expect from heavy-quark spin symmetry of the NRQCD Lagrangian [5] that the matrix-element for ${}^1S_0^{[8]} \to h_c$ should be of the same order as that for ${}^3S_1^{[8]} \to {}^3P_1$. This is because the essential difference between these transitions comes through the magnetic quantum number so that the corrections to this equality will be of $O(v^2) \sim 30\%$. For the derivative of the wave-function we use a similar argument to fix it to be the same as for the χ_c states.

We have computed the cross-sections for the Tevatron energy $\sqrt{s} = 1.8$ TeV. In Fig. 1, we present the ${}^1P_1$ production cross-section $d\sigma/dp_T$ as a function of p_T, where the cross-section has been folded in with the branching ratio of the ${}^1P_1$ state into $J/\psi + \pi$. We have integrated over the full rapidity interval $-0.6 \le y \le 0.6$ covered by the CDF experiment. For the results shown in Fig. 1, we have used the MRSD$-'$

densities [19]. The parton densities are evolved to a scale $Q = M_T/2$. For the singlet matrix element, we use the value extracted from χ_c decays, which is $\left\langle \mathcal{O}_1^{h_c}(^1P_1) \right\rangle = 0.32$ [18] and for the octet matrix element we have $\left\langle \mathcal{O}_8^{1P1}(^1S_0) \right\rangle = 0.0098$ [9]. With these inputs, we find that the cross-section for h_c production (folded in with the decay fraction into a J/ψ and π, which we take to be 0.5% [15]) integrated over the region between 5 and 20 GeV in p_T is quite substantial. With the 20 pb^{-1} total luminosity accumulated at the Tevatron, we expect of the order of 650 events in the $J/\psi + \pi$ channel. Of this the contribution from the colour-singlet channel is a little more than 40, while the octet channel gives more than 600 events. The colour-octet dominance is more pronounced at large-p_T. The octet contribution has a flatter p_T dependence as compared to the singlet which falls off rather rapidly with p_T. The shape of the p_T distribution is also, therefore, a testable prediction of NRQCD.

We have studied the effect on the cross-section of the variation of the parton densities, the scale and the non-perturbative matrix-elements. By using GRV densities [20] instead of MRSD$-'$, we find that the cross-section increases by about 20-25%. Varying the scale from $M_T/2$ to $2M_T$ reduces the predictions by roughly a factor of 2. A 25% variation results if we vary the colour-octet matrix element by 30% around the central-value quoted above. The decay branching fraction of h_c into a $J/\psi + \pi$ could be as large as 1%, and if we use this instead of the 0.5% used in the above calcuations we could have a production cross-section which is twice as large.

Before we conclude, a few remarks about this remarkable prediction of NRQCD is in order. There is now sufficient empirical evidence for the failure of the colour-singlet model and the need to include effects beyond this model. NRQCD provides a suitable way of going beyond the colour-singlet model and, as discussed, has had considerable success in describing a large amount of data on quarkonium decay and production. There however exists a different approach to quarkonium production the so-called colour-evaporation model or, alternatively called, the semi-local duality model [21]. The idea in this model is to relate the integral of the open-charm production cross-section to the sum of the resonance production cross-sections. The individual resonance cross-sections are not predicted but are obtained by fitting a parameter to experimental data. Detailed results of this model for hadroproduction of J/ψ have been obtained recently [22, 23] and the comparison with the data is as successful as that of NRQCD. But we must bear in mind that NRQCD is a more predictable model. In particular, when some of the non-perturbative parameters have been determined from experiment it is possible to use symmetry relations to estimate other non-perturbative parameters. This is true of the production process under consideration in this paper. We are, therefore, able to predict the number of h_c events that we will see at the Tevatron, which is not predicted in any semi-local duality based approach, where the undetermined parameters can only be fitted *a posteriori*.

In conclusion, we find that a reasonably large rate for the production of the $^1P_1$ is expected at the Tevatron, with a dominant contribution from the colour-octet pro-

duction channel. Heavy-quark symmetry relations allow us to infer the size of the non-perturbative matrix-elements and to predict the rate for h_c production and its subsequent decay into a J/ψ and a π. By looking at J/ψ events associated with a soft pion, it should be possible to pin down the elusive ${}^1P_1$ resonance at the Tevatron, given the large number of J/ψ events already available. We believe that this is a firm prediction of the NRQCD framework and may be a useful way of distinguishing this from other models of quarkonium formation.

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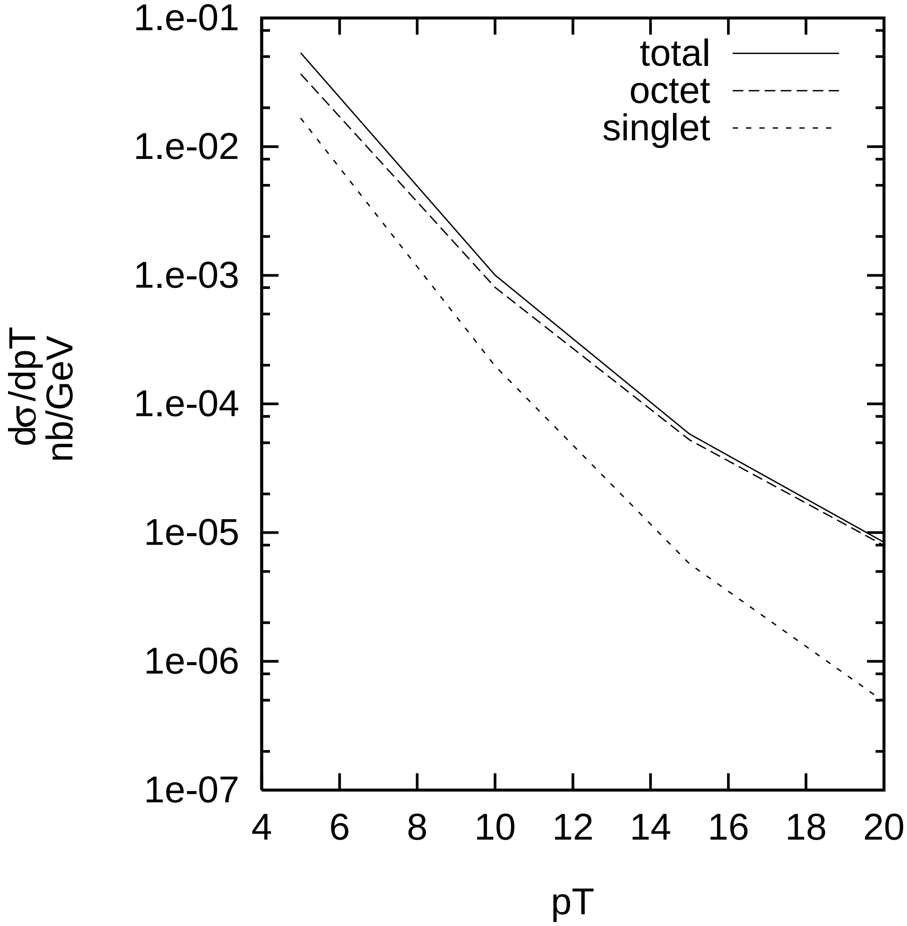

Figure 1: $d\sigma/dp_T$ (in nb/GeV) for h_c production (after folding in the decay branching fraction of the h_c into a $J/\psi + \pi$) at 1.8 TeV c.m. energy with $-0.6 \leq y \leq 0.6$. The colour-singlet, colour-octet and the total contributions are shown.